

# Neutrino Interactions with Nuclei

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**Abstract.** We investigate neutrino-nucleus collisions at intermediate energies incorporating quasi-elastic scattering and the excitation of 13 resonances as elementary processes, taking into account medium effects such as Fermi motion, Pauli blocking, mean-field potentials and in-medium spectral functions. A coupled-channel treatment of final state interactions is achieved with the GiBUU transport model. Results for inclusive reactions, neutrino- and electron-induced, as well as for pion production and nucleon knockout are presented.

**Keywords:** neutrino-nucleus interactions, quasi-elastic scattering, resonance excitation, pion production, nucleon knockout

**PACS:** 13.15.+g, 25.30.Pt, 25.30.-c, 23.40.Bw, 24.10.Lx, 24.10.Jv

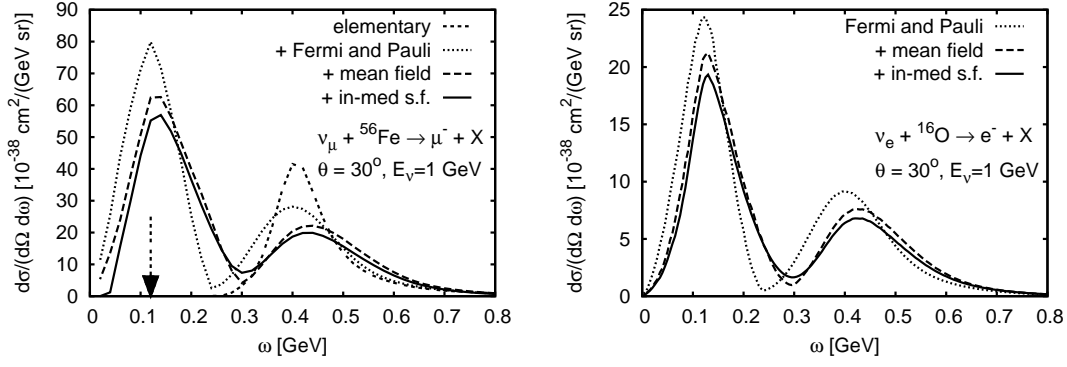
The study of neutrino interactions with nuclei is crucial for current and future oscillation experiments. The main goal is to improve our knowledge of the energy fluxes, backgrounds and detector responses in order to minimize systematic uncertainties. Most of the experiments are performed on nuclear targets, thus, an understanding of nuclear effects is essential for the interpretation of the data.

Here we report on an application to such processes with a model that has been well tested on other nuclear reactions, such as heavy-ion collisions, proton- and pion-induced reactions on nuclei and photonuclear reactions, using the same theoretical input and the same code: the Giessen BUU model (GiBUU). The model treats the nucleus as a local Fermi gas of nucleons with the total reaction rate given by an incoherent sum over all nucleons embedded in a nuclear medium (impulse approximation). For more details, we refer the reader to our earlier work [1, 2].

At neutrino energies ranging from 0.5 – 2 GeV, the relevant contribution to the cross section is quasi-elastic (QE) scattering ( $\nu N \rightarrow lN'$ ) and pion production ( $\nu N \rightarrow l\pi N'$ ). The latter is dominated by the excitation of the  $\Delta$  resonance and its subsequent decay ( $lN \rightarrow l'\Delta \rightarrow l'\pi N'$ ) - however, with increasing neutrino energy also higher resonances contribute significantly to pion production. The cross section for QE scattering and resonance excitation on a bound nucleon is given by

$$\frac{d\sigma_{QE,RES}}{d\omega d\Omega} = \frac{1}{32\pi^2} \frac{|\mathbf{k}'|}{k \cdot p} \mathcal{A}(E', \mathbf{p}') C_{CC,NC} L_{\mu\nu} H_{QE,RES}^{\mu\nu}, \quad (1)$$

where we use the following notation: a lepton with four-momentum  $k = (E_V, \mathbf{k})$  scatters off a nucleon with momentum  $p = (E, \mathbf{p})$ , going into a lepton with momentum  $k' = (E_{l'}, \mathbf{k}')$  and a nucleon/resonance with  $p' = (E', \mathbf{p}')$ . We further define the transferred energy  $\omega = E_V - E_{l'}$  and the solid angle  $\Omega = \angle(\mathbf{k}, \mathbf{k}')$ . The dynamics of the interaction is incorporated in the leptonic ( $L_{\mu\nu}$ ) and hadronic ( $H_{QE,RES}^{\mu\nu}$ ) tensor with the appropriate coupling  $C_{CC,NC}$ .

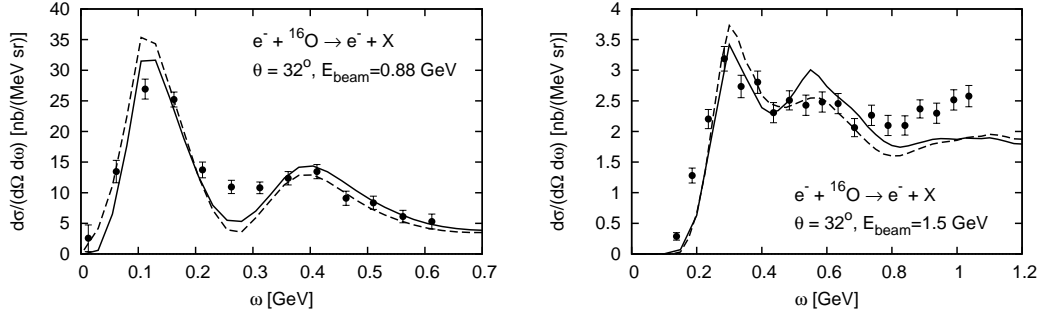


**FIGURE 1.** Inclusive CC cross section  $d\sigma/d\omega d\Omega$  on  $^{56}\text{Fe}$  and  $^{16}\text{O}$  as a function of the energy transfer  $\omega = E_\nu - E_\ell$  at a  $E_\nu = 1$  GeV and scattering angle of  $\theta = 30^\circ$ . The short-dashed line denotes our result for the free case (left panel only), the dotted line includes Fermi motion and Pauli blocking only. The long-dashed line denotes the result, where we take into account also the binding in a density and momentum dependent mean-field potential. The solid line includes in addition the in-medium spectral function (SF).

For QE scattering, we use the standard expression for  $H_{QE}^{\mu\nu}$  (cf. e.g. our earlier work in Ref. [1]) with the BBBA-2005 vector form factors [4] and a dipole ansatz with  $M_A = 1$  GeV for the axial ones. For the resonance excitation, we have considered, besides the dominant  $\Delta$  ( $P_{33}(1232)$ ) resonance, 12 higher resonances, namely  $P_{11}(1440)$ ,  $D_{13}(1520)$ ,  $S_{11}(1535)$ ,  $S_{31}(1620)$ ,  $S_{11}(1650)$ ,  $D_{15}(1675)$ ,  $F_{15}(1680)$ ,  $D_{33}(1700)$ ,  $P_{13}(1720)$ ,  $F_{35}(1905)$ ,  $P_{31}(1910)$  and  $F_{37}(1950)$ . Following Refs. [5, 6], we relate the vector form factors to helicity amplitudes for which we use the results of the recent MAID analysis [7] while the axial form factors follow a modified dipole ansatz with an axial coupling obtained with the assumption of PCAC and pion-pole dominance.

The nucleons are embedded in a nucleus which is treated within a local Thomas-Fermi approximation as a Fermi gas of nucleons bound by a density and momentum dependent mean-field. The density profiles are based on data from electron scattering and Hartree-Fock calculations. The presence of a momentum-dependent mean field leads to the appearance of effective masses in Eq. (1).  $M$  denotes the effective mass of the incoming nucleon  $N$ , defined as  $M = M_N + U_{S_N}(\mathbf{p}, \mathbf{r})$ , where  $M_N$  denotes its vacuum mass and  $U_{S_N}(\mathbf{p}, \mathbf{r})$  the scalar potential. The spectral function  $\mathcal{A}(E', \mathbf{p}')$  includes the effect of the momentum-dependent potential on the outgoing particle and also accounts for the in-medium collisional broadening of the outgoing final states. More details can be found in Ref. [2].

In Fig. 1, we present results for the CC reaction  $^{56}\text{Fe}(\nu_\mu, \mu^-)X$  for a neutrino beam energy of 1 GeV and a lepton scattering angle of  $30^\circ$  (left panel) and for  $^{16}\text{O}(\nu_e, e^-)X$  (right panel). One observes a broadening and a shift of the QE and pion peak caused by Fermi motion, the momentum-dependent potential and the in-medium width of the nucleon and the resonances. As a necessary check of our calculations we have obtained within the same model also electron-induced inclusive cross sections. In these calculations we have omitted the axial parts of the hadronic currents and included in addition non-resonant single-pion background [2]. The results for  $^{16}\text{O}(e^-, e^-)X$  are shown in Fig. 2 for two different energies. The overall agreement with the data is very



**FIGURE 2.** Same as Fig. 1 but for the electron-induced inclusive reaction  $^{16}\text{O}(e^-, e^-)X$  at a fixed electron energy and scattering angle of  $\theta = 32^\circ$ . The data are taken from Ref. [8].

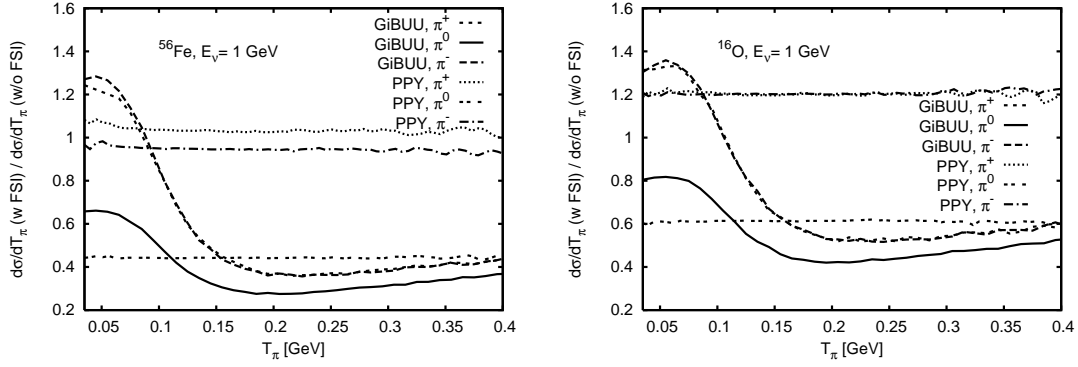
good and comparable to that in Ref. [3]. The agreement is improved, in addition to using a local Fermi gas, by including a mean field and in-medium spectral functions.

Besides inclusive reactions, also semi-inclusive processes where, in addition to the outgoing lepton in the  $\nu A$  reaction, one or more pions, nucleons etc. are detected are experimentally accessible. In particular for NC reactions one has to rely on the modeling of these reactions since the outgoing neutrino is not detected. In our description, we treat the exclusive reaction as a two step process: once the initial interaction has taken place, the final state particles are transported out of the nucleus. These final state interactions (FSI) are implemented by means of the coupled-channel GiBUU transport model [9] based on the BUU equation

$$(\partial_t + \nabla_p H \cdot \nabla_r - \nabla_r H \cdot \nabla_p) F_i(\mathbf{r}, \mathbf{p}, \mu; t) = I_{\text{coll}}[F_i, F_N, F_\pi, F_\Delta, \dots].$$

This equation describes the space-time evolution of the generalized phase space density  $F_i(\mathbf{r}, \mathbf{p}; t)$  of particles of type  $i$  with invariant mass  $\mu$  under the influence of the Hamiltonian  $H$ . The BUU equations are coupled via the mean field in  $H$  and via the collision term  $I_{\text{coll}}$ . The collision integral  $I_{\text{coll}}$  accounts for elastic and inelastic collisions, decays and the formation of resonances, including Pauli blocking. FSI therefore lead to absorption, charge exchange, a redistribution of energy and to the production of new particles.

The impact of FSI effects on NC induced pion production is clearly visible in the ratios obtained by dividing the kinetic energy spectra with FSI by the one without FSI (cf. curves in Fig. 3 labeled "GiBUU"; see Ref. [1] for details). The absorption is bigger for  $^{56}\text{Fe}$  (left panel) than for  $^{16}\text{O}$  (right panel), as expected. For pions with kinetic energy above  $\approx 0.1$  GeV we find large effects of FSI, with especially strong suppression around  $T_\pi \approx 0.13$  GeV. This is the region where pion absorption and rescattering are most prominent due to the excitation of the  $\Delta$  resonance ( $\pi N \rightarrow \Delta$  followed by  $\Delta N \rightarrow NN$ ,  $\Delta NN \rightarrow NNN$ ,  $\Delta N \rightarrow \pi NN$  or  $\Delta N \rightarrow \Delta N$ ). At lower pion energies we find a peak because pions of higher energy in average loose energy via  $\pi N$  rescattering. Since side-feeding shifts strength always from the dominant into the less dominant channel we find that FSI lead to a strong reduction of the total yield in the  $\pi^0$  channel (solid line) while the reduction is much smaller in the  $\pi^+$  and  $\pi^-$  channels (dashed lines); there the ratio even exceeds 1 at low kinetic energies. A similar pattern has been experimentally observed in pion photoproduction (cf. Fig. 16 in Ref. [10]). The particular dependence of both ratios reflects well-known features of the  $\pi N \Delta$  dynamics in nuclei.

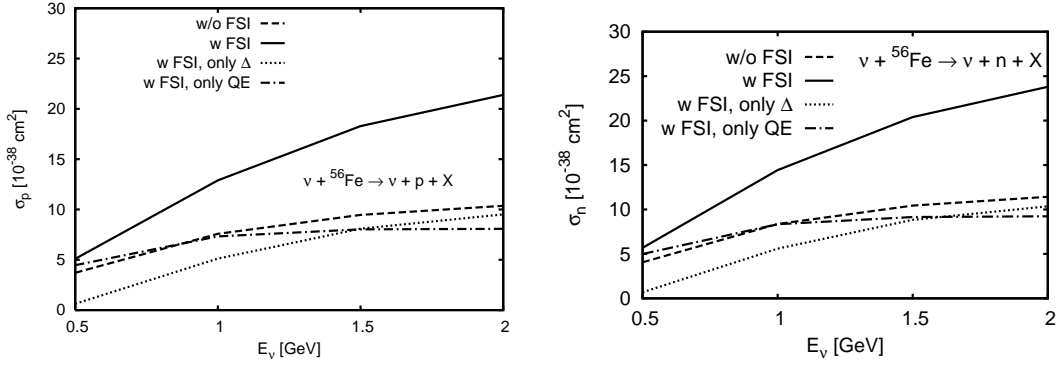


**FIGURE 3.** Ratio of the NC differential cross section (the cross section with FSI divided by the one without FSI) for NC pion production on  $^{56}\text{Fe}$  (left) and  $^{16}\text{O}$  (right) versus the pion kinetic energy for  $E_v = 1$  GeV. The initial QE scattering process has been "switched off". The curves labeled "PPY" denote the results of Paschos *et al.* [11, 12].

The curves in Fig. 3 labeled with "PPY" give the corresponding results obtained from a calculation of Paschos *et al.* [11, 12]. In this article we compare with the corrected results of Ref. [12]<sup>1</sup> where we divided their "ig" result (with only Pauli-blocking) by their "f" result (with all nuclear corrections) and rescaled  $E_\pi$  to  $T_\pi$ . We now focus on the comparison of both FSI models, the ANP model [13] used by Paschos *et al.* and our GiBUU model. We find that both FSI models are quantitatively and even qualitatively very different ("GiBUU" vs. "PPY" curves). The ratios of Paschos *et al.* for the charged pions are considerably larger than ours for kinetic energies  $> 0.1$  GeV. In addition, they are practically flat as a function of the pion energy, in contrast to our results. In our calculation the ratio is much larger at low pion energies than at the higher ones because pions rescatter with the nucleons (with or without charge exchange) in the nuclear medium; in doing so they lose energy. After the first collision, due to the energy redistribution, the probability of a second collision changes. The ANP model, on the contrary, assumes that the energy of the pion is constant during its random walk through the nucleus. Also, the ANP model uses vacuum cross sections to estimate the collision probability ignoring in-medium modifications. This is especially important for pions in the  $\Delta$  region since this resonance is considerably broadened in the medium.

A correct understanding of the in-medium  $\pi N \Delta$  dynamics is crucial for the interpretation of experiments to ensure proper identification of QE events. This is visualized in Fig. 4 where we show the NC induced cross sections for proton and neutron knockout on  $^{56}\text{Fe}$ . The solid lines, showing the results with FSI included, lie in both cases clearly above the ones without FSI (dashed lines); this enhancement is caused by secondary interactions. Furthermore, it is indicated whether the knockout was induced by initial QE scattering (dash-dotted) or  $\Delta$  excitation (dotted) through e.g.  $\Delta N \rightarrow NN$ ,  $\Delta \rightarrow \pi N$ ,  $\Delta NN \rightarrow NNN$ . Both contribute to the cross section above  $E_v \approx 1.2$  GeV with almost equal amounts. If an initially produced pion gets absorbed, then this event looks "QE-like" which can lead to systematic errors in the data analysis. This is particularly critical

<sup>1</sup> The original work [11] has an error in the elementary pion production cross section.



**FIGURE 4.** Integrated cross section for NC induced proton (left) and neutron (right) knockout on  $^{56}\text{Fe}$  versus  $E_\nu$ . The dashed lines show the results without FSI; the results denoted by the solid lines include FSI. Also indicated is the contribution of QE (dash-dotted) and  $\Delta$  excitation (dotted) to the total yield. Multi-nucleon knockout is taken into account.

for the NC case, where the outgoing neutrino remains undetected. Only for neutrino energies up to  $\approx 0.5$  GeV one can neglect the resonance contributions to nucleon knockout.

We conclude that with the present knowledge of  $\pi N\Delta$  dynamics in nuclei, based on extensive studies of pion and photo-nuclear reactions, a realistic, quantitative description of neutrino induced pion production in nuclei is possible. In-medium effects in  $\nu A$  scattering, and in particular FSI, are important for the interpretation of LBL oscillation experiments. The influence of final state interactions, therefore, has to be treated with the same degree of sophistication as the primary production process and the nuclear spectral function information.

We thank all members of the GiBUU project for cooperation. This work has been supported by the Deutsche Forschungsgemeinschaft and by BMBF.

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